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Selected Test Results from the Encell Technology Nickel Iron Battery

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Abstract

The performance of the Encell Nickel Iron (NiFe) battery was measured. Tests included capacity, capacity as a function of rate, capacity as a function of temperature, charge retention (28-day), efficiency, accelerated life projection, and water refill evaluation. The goal of this work was to evaluate the general performance of the Encell NiFe battery technology for stationary applications and demonstrate the chemistry's capabilities in extreme conditions. Test results have indicated that the Encell NiFe battery technology can provide power levels up to the 6C discharge rate, ampere-hour efficiency above 70%. In summary, the Encell batteries have met performance metrics established by the manufacturer. Long-term cycle tests are not included in this report. A cycle test at elevated temperature was run, funded by the manufacturer, which Encell uses to predict long-term cycling performance, and which passed their prescribed metrics.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. Imre Gyuk and the Office of Electricity for funding Phase I of this work.

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NOMENCLATURE

Ah	ampere-hour
DOE	Department of Energy
NiFe	nickel iron
SNL	Sandia National Laboratories
V	volt
Wh	watt-hour

1. INTRODUCTION

The work for this project was partially funded through the Department of Energy (DOE) Office of Electricity and partially funded through Encell Technology, Inc. The objectives of the project are consistent with the DOE energy programs goals in the following areas:

- Development and evaluation of integrated electrical energy storage systems;
- Analysis and comparison of technologies and applications; and
- Encouraging program participation by industry, academia, research organizations and regulatory agencies.

The work reported in this paper is part of our effort to characterize the performance parameters of advanced batteries. The Encell nickel iron (NiFe) battery technology has recently entered the battery market. Encell's initial target markets are stationary applications such as micro-grid, solar, wind, and geothermal back-up energy storage. The NiFe battery chemistry was introduced in 1908 and used in large vehicles and stationary applications. The NiFe battery's advantages are durability and long life. The historical NiFe technology's notable limitations include low specific energy, low power, low charge retention and poor low temperature performance along with being high cost[1] and is still in limited mass production throughout the world today for specific applications. NiFe battery chemistry is known for its robustness, extreme shelf and cycle life. The historical NiFe technology that was most robust to abuse also had limitations in being heavy, low power, low charge retention and poor low temperature performance along with being high cost. Thus, over the years, other nickel battery technologies (e.g., NiCd, NiMH, NiZn, and NiH_2) have displaced NiFe in many applications.

Encell has developed their NiFe battery to deliver significant advances from the original Edison 1900s technology and addressed the historical shortcomings of the technology. In this paper, the performance of Encell's NiFe cell was evaluated using capacity testing at various rates, capacity as a function of temperature, charge retention, deionized water refilling/maintenance requirements and accelerated life testing to evaluate modeled cycle life.

2. TEST SUMMARY

The cell test procedures used in this testing effort were initially developed as part of a plan to test the general characteristics, robustness at various temperatures and cycle life of the Encell NiFe cell. Prior to completing the defined characterization tests, baseline cycles were performed on the battery to confirm there were no damages to the battery pack during shipping and handling. The seven following characterization tests used are itemized below:

- Capacity– Establishes a capacity of the battery pack at a defined discharge rate.
- Rate Capability – Establishes the rate capability of the battery at various discharge rates (C-rate, 2C and 6C).
- Temperature – Establishes capacity of the battery pack at various temperatures (0°C, 40°C, and 80°C).
- 28-Day Charge Retention – Establishes the percentage of self-discharge at rest in a charged state.
- Efficiency – Establishes efficiency at a given charge/discharge rate.
- Refill/Gassing – Evaluates the maintenance requirements (refilling of deionized water) of the cell at a defined charge/discharge regime.
- Accelerated Life – Evaluates cycle life under an accelerated test regime.

All testing was performed on a 12 volt (V), 140 amp-hour (Ah) battery pack system. Testing was completed in two phases and were funded in the first round by DOE and in the second by Encell, with accelerated cycling funded by Encell. Table 1 summarizes the Encell NiFe cell specifications of this design. Table 2 summarizes the Phase I and Phase II Test programs. The testing procedures and battery specifications as defined by Encell are listed in Section 2.0. Phase I and Phase II testing results are summarized in Section 3.0.

Table 1. Cell Specifications

Operating Voltage Window	1.0V - 1.7V
Max Voltage	1.7V
Discharge End Voltage (0.1C Rate)	1.0V
Ah Capacity (0.1C rate, 25°C)	140Ah
Maximum Charge Current	70A
Maximum Discharge Current	840A
Maximum Operating Temperature, °C	80
Minimum Operating Temperature, °C	0
Charge Retention (25°C)	90%
Wh Efficiency (0.1C rate, 25°C)	70%

Table 2. Test Plan

Phase I Test Program		
Regime	**Cycles**	**Specified capacity**
Charge: C/2 (70 A) for 210 Ah Rest (1): 0 rest Discharge: C/10 (14 A) to 10 V Rest (2): 15 minutes	3 cycles	>133 Ah
Charge: C/2 (70 A) for 210 Ah Rest (1): 0 rest Discharge: C-rate (140 A) to 5 V Rest (2): 30 minutes	3 cycles	>106.4 Ah
Charge: C/2 (70 A) for 210 Ah Rest (1): 0 rest Discharge: C/10 (14 A) to 8 V Rest (2): 30 min rest	15 cycles	>106.4 Ah
Charge: C/2 (70 A) for 210 Ah Rest (1): 0 rest Discharge: C/10 (14 A) to 10 V Rest (2): 30 min rest	3 cycles	>133 Ah
Charge: C/2 (70 A) for 252 Ah Rest (1): 28 days Discharge: C/10 (14 A) to 8 V Rest (2): N/A	1 cycle	>119.7 Ah
Charge: C/2 (70 A) for 112 Ah Rest (1): 30 min rest Discharge: C/10 (14 A) to 10 V Rest (2): 30 min rest	30 cycles without refill	30 cycles without refill
Charge: C/2 (70 A) for 112 Ah (80%) Rest (1): 0 rest Discharge: C/2 (70 A) to 10 V Rest (2): 15 min rest	60 days or until Capacity is below 14 Ah	125 cycles with capacity > 14 Ah
Phase II Test Program		
Regime	**Cycles**	**Specified capacity**
Charge: C/2 (70 A) for 210 Ah Rest (1): 0 rest Discharge: 2C (280 A) to 8 V Rest (2): Sufficient time to cool to 25°C (±5°C)	3 cycles	>106.4 Ah
Charge: C/2 (70 A) for 210 Ah (150%) Rest (1): 0 rest Discharge: 6C (840 A) x 30 Ah (or 4.0 V) Rest (2): Sufficient time to cool to RT (±5°C)	3 cycles	>14 Ah
Charge: C/2 (70 A) for 210 Ah (150%) Rest (1): 0 rest Discharge: C/10 (14 A) x 8 V Rest (2): 30 min rest	15 cycles	>106.4 Ah
Charge: C/5 (28 A) for 192Ah (137%) Rest (1): 0 rest Discharge: C/10 (14 A) x 8.0 V Rest (2): Sufficient time to cool to 80°C (±5°C)	3 cycles	>106.4 Ah
Charge: C/2 (70 A) for 252 Ah (180%) Rest (1): 28 days Discharge: C/10 (14 A) x 8 V Rest (2): 15 min rest	1 cycle	>119.7 Ah

2.1 Phase I Testing

Phase I testing was conducted in 2013 and included:

- Capacity Test
- Rate Capability: C-rate Discharge
- Temperature Tests: 0°C, 40°C
- 28-Day Charge Retention
- Efficiency Profile
- Refill/Gassing Test and
- Accelerated Life Test.

The 2C Rate Capacity, the 6C Rate Capacity and 80°C Temperature tests were cancelled during Phase I due to thermal issues. Phase I, with the exception of Accelerated Life testing, was funded by the DOE.

The Phase I plan and specified performance was provided by Encell Technology, Inc. Figure 1 is a photograph of the 12V, 140 Ah battery pack that was tested under Phase I. The battery pack dimensions were 12.8" H x 10.3" D x 21.9" W without measuring the metal casing or the manifold added after the fact to provide headroom for bubbling of electrolyte and to vent evolved hydrogen. The running battery with manifold is pictured in Figure 2.

Figure 1. Encell Phase I Battery pack as received for testing.

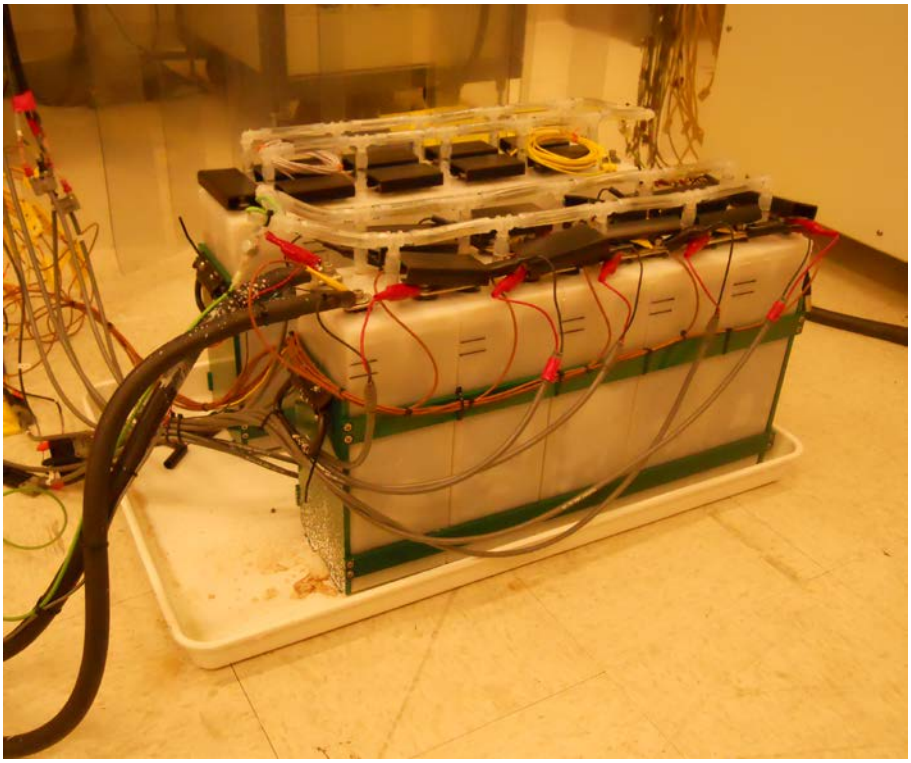

Figure 2. Encell Phase I Battery pack modified with manifold and under test.

2.2 Phase II Testing

Sandia received new test samples with design updates for Phase II testing in January 2014. Phase II testing was conducted in 2014 and included:

- Rate Capability: 2C Discharge, 6C Discharge
- Temperature Tests: 0°C, 80°C
- 28-Day Charge Retention

Tests completed in Phase II were either those that fell below the acceptance criteria during Phase I (i.e., 0°C Temperature Test and 28-Day Charge Retention Test) or those that were canceled during the first phase of testing (2C Discharge, 6C Discharge and 80°C Temperature Test). Phase II testing was run under a work for others from Encell.

The test plan for Phase II was provided by Encell Technology, Inc. on January 21, 2014. Battery specifications remain the same in Phase II, consistent with that defined during Phase I.

In Phase II, the design was changed to have two cells in parallel, with 10 cell pairs in series, still rated at 140 Ah. A schematic of this battery is shown in Figure 3, and a picture shown in Figure 4. The dimensions were 12.8” H x 10.6” D x 21.9” W.

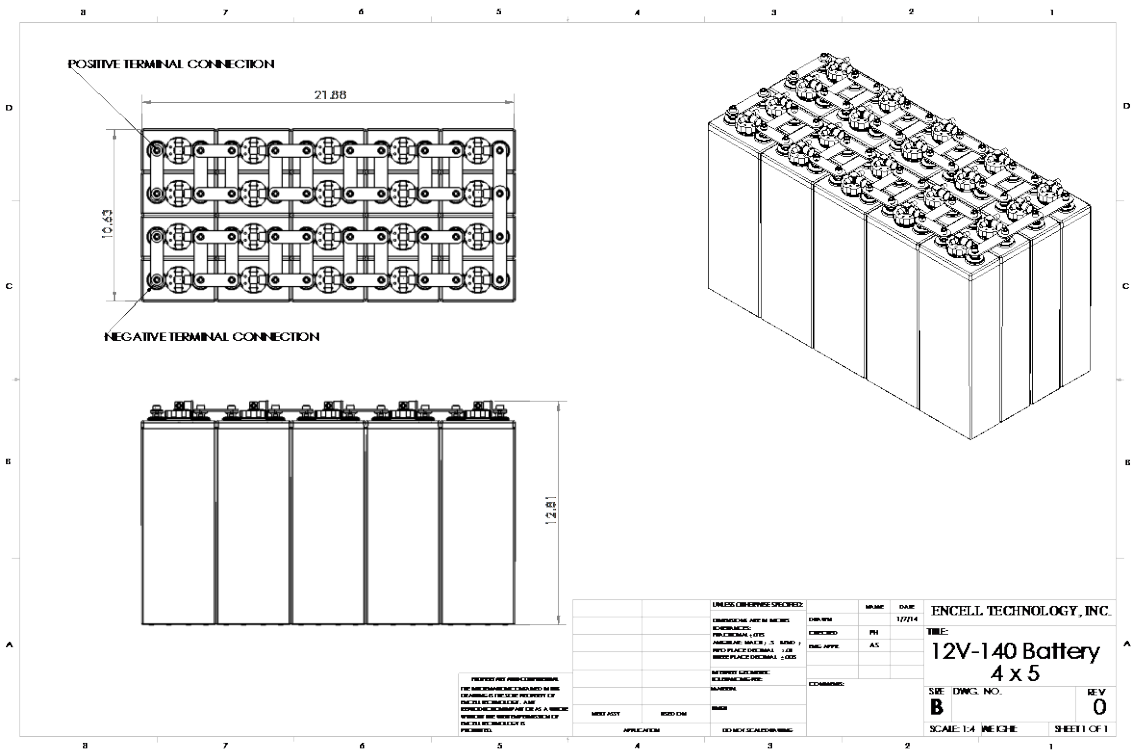

Figure 3. Encell Phase II Battery pack design.

Figure 4. Encell Phase II Battery pack.

A watering manifold was added in the Phase II design that made watering the battery simpler. The manifold had an automatic shutoff on each cell as the cell was filled, with one manifold serving 10 cells.

3. TEST PROCEDURES

This section summarizes each of the test sequences included in the program. Table 2 provides a summary of the tests completed in Phase I and Phase II and the criteria for each test as defined by Encell before starting the test program.

3.1 Capacity Test

The capacity test is used to determine the battery capacity at a defined standard discharge rate. This test is done prior to other testing to establish a baseline capacity for the battery pack. This will help identify how the various conditions affect the battery capacity. The battery shall be tested for its capacity at 0.1C discharge rate as follows:

1. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
2. The battery shall not rest at open circuit between charge and discharge.
3. The battery shall be discharged at 0.10C (14 A) until the end voltage of 10V is reached. The ampere-hour and watt-hour (Wh) capacity of the cell shall be measured.
4. The battery shall rest at open circuit for 15 minutes.
5. Steps 1 to 5 shall be repeated 3 times.

Specified capacity is 133 Ah at this rate.

3.2 Discharge Rate Capability

The discharge rate capability test evaluates the capacity of the battery at various discharge rates. The discharge rates performed included C-rate, 2C and a 6C discharge rate test and are described herein.

3.2.1 C-Rate Discharge

The C-rate discharge rate capability test was defined as follows:

1. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
2. The battery shall not rest at open circuit between charge and discharge.
3. The battery shall be discharged at C (140 A) until the end voltage of 5V is reached. The Ah and Wh capacity of the cell shall be measured.
4. The battery shall rest at open circuit for 30 minutes.
5. Steps 1 to 5 shall be repeated 3 times.

Specified capacity for the C-rate Discharge Test is 106.4 Ah.

3.2.2 2C Discharge

The 2C discharge rate capability test was defined as follows:

1. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
2. The battery shall not rest at open circuit between charge and discharge.

3. The battery shall be discharged at 2C (280 A) until the end voltage of 8V is reached. The Ah and Wh capacity of the cell shall be measured.
4. The battery shall rest at open circuit for sufficient amount of time to cool to room temperature (25°C ± 5°C).
5. Steps 1 to 5 shall be repeated 3 times.

Specified capacity for the 2C Discharge Test is 106.4 Ah.

3.2.3 6C Discharge

During Phase II, the 6C discharge rate capability test was performed as follows:

1. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
2. The battery shall not rest at open circuit between charge and discharge.
3. The battery shall be discharged at 6C (840 A) until the end Ah capacity of the battery reaches 30 Ah or a voltage of 4V is reached, whichever is sooner. The Ah and Wh capacity of the cell shall be measured.
4. The battery shall rest at open circuit for a sufficient amount of time for the battery to cool to room temperature (25°C ± 5°C).
5. Steps 1 to 5 shall be repeated 3 times.

Specified capacity for the 6C Discharge Test is 14 Ah.

Note: the test sequence for Cycles 2 and 3 were modified from the referenced Phase II test plan. The charge input for Cycles 2 and 3 was decreased to 100 Ah (from 210 Ah). This was done to account for residual charge remaining in the module due to the discharges being terminated at 30 Ah.

3.3 Temperature Test

The temperature test evaluates the capacity of the battery at various temperatures (0°C, 40°C and 80°C). All temperature tests were performed within an environmental temperature chamber set at the defined temperature with the battery left to equilibrate at temperature before initiating test.

3.3.1 0°C Temperature Test

The test sequence for the 0°C Temperature Test is described herein:

1. The battery pack shall be placed into the environmental chamber set at 0°C for equilibration to temperature. Testing will commence once the battery is confirmed at the defined temperature.
2. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
3. The battery shall not rest at open circuit between charge and discharge.
4. The battery shall be discharged at 0.1C (14 A) until the end voltage of 8V is reached.
5. The battery shall rest at open circuit for 30 minutes.
6. The Ah and Wh capacity of the cell shall be measured.
7. Steps 2 to 6 shall be repeated 15 times.

Specified capacity for the 0°C Temperature Test is 106.4 Ah.

3.3.2 40°C Temperature Test

The test sequence for the 40°C Temperature Test is described herein:

1. The battery pack shall be placed into the environmental chamber set at 40°C for equilibration to temperature. Testing will commence once the battery is confirmed at the defined temperature.
2. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 210 Ah.
3. The battery shall not rest at open circuit between charge and discharge.
4. The battery shall be discharged at 0.1C (14 A) until the end voltage of 10V is reached.
5. The battery shall rest at open circuit for 30 minutes.
6. The Ah and Wh capacity of the cell shall be measured.
7. Steps 2 to 6 shall be repeated 3 times.

Success capacity for the 40°C Temperature Test is 133 Ah.

3.3.3 80°C Temperature Test

The 80°C Temperature Test completed during Phase II is described herein:

1. The battery pack shall be placed into the environmental chamber set at 80°C for equilibration to temperature. Testing will commence once the battery is confirmed at the defined temperature.
2. The battery pack shall be charged at 0.2C (28 A) to an Ah input of 192 Ah.
3. The battery shall not rest at open circuit between charge and discharge.
4. The battery shall be discharged at 0.1C (14 A) until the end voltage of 8V is reached.
5. The battery shall rest at open circuit for 30 minutes or sufficient time to cool to 80°C.
6. The Ah and Wh capacity of the cell shall be measured.
7. Steps 2 to 6 shall be repeated 3 times.

Success capacity for the 80°C Temperature Test is 106.4 Ah.

3.4 28-Day Charge Retention

The test sequence for the 28-Day Charge Retention test is described herein:

1. The following test is to be performed within an environmental chamber maintained at 25°C for the entirety of the test.
2. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 252 Ah
3. The battery shall rest at open circuit between charge and discharge for a period of 28 days.
4. The battery shall be discharged at 0.1C (14 A) until the end voltage of 8V is reached.
5. The Ah and Wh capacity of the cell shall be measured.

Specified capacity for the 28-Day Charge Retention Test is 119.7 Ah.

3.5 Gassing/Refilling

The gassing (hydrogen)/refill test was performed to confirm the amount of water replenishment needed after a 30-day period with one cycle per day (30 cycles) at a defined charge and discharge rate. The test sequence for this test is described herein:

1. Confirm electrolyte level is full before starting test sequence.
2. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 112 Ah.
3. The battery shall rest at open circuit for 30 minutes between charge and discharge.
4. The battery shall be discharged at 0.1C (14 A) until the end voltage of 10V is reached.
5. The battery shall rest at open circuit for 30 minutes.
6. Steps 2 to 5 shall be repeated 30 times.
7. Measure the electrolyte level 4 hours following the termination of the final discharge.

Specified performance for the Gassing/Refilling Test is 30 cycles without refill, and electrolyte level is above the refill line when measured 4 hours following last discharge cycle.

3.6 Accelerated Life Testing

Accelerated life testing was performed to predict the cycle life of the NiFe chemistry. The test regime was developed by Encell Technology, Inc. Based on the test results, cycle life is predicted using a proprietary accelerated life test model. The test sequence for this test is described herein:

1. The following test is to be performed within an environmental chamber maintained at 55°C for the entirety of the test.
2. The battery pack shall be charged at 0.5C (70 A) to an Ah input of 112Ah.
3. The battery shall not rest at open circuit between charge and discharge.
4. The battery shall be discharged at 0.5C (70 A) until the end voltage of 10V is reached.
5. The battery shall rest at open circuit for 15 minutes.
6. Steps 2 to 5 shall be repeated for 60 days or until discharge capacity is below 14 Ah.
7. The following items shall be measured during the test: Ah and Wh capacity for each cycle, midpoint voltage on discharge for each cycle, continuous temperature, time, cycle and amounts of refilling with deionized water.

Specified capacity for the Accelerated Life Test is 125 cycles with a capacity above 14 Ah. This predicts +3,000 cycles at application conditions (C/4 Charge, C/8 Discharge, 6-hour rest between cycles, 25°C, 100% discharge to 1.0V/cell, and 80% SOC) with capacity above 70%.

4. TEST RESULTS

Test results of Phase I and Phase II testing are included in this section.

4.1 Phase I Test Results

Four battery packs (referred to here as Packs A, B, C, and D) were used to complete the Phase I test program. The Phase I test summary is included in Section 2.0. Test procedures are outlined in Section 3.0.

4.1.1 Capacity Test

Figure 5 shows the Ah capacity and voltage ranges of Pack C. Results were above the specified capacity of 133 Ah.

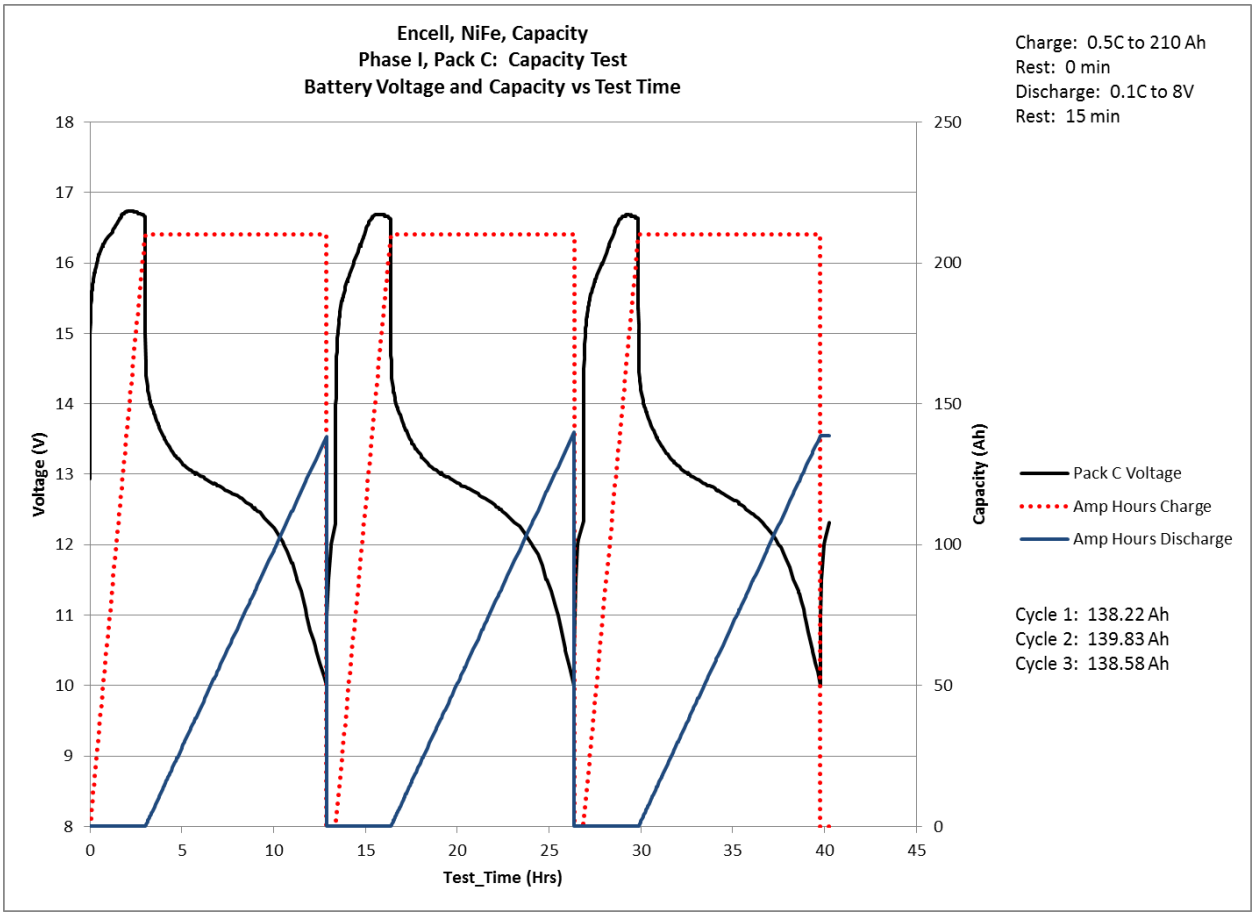

Figure 5. Capacity Test Results

4.1.2 C-Rate Discharge Rate Capability

Figure 6 shows the Ah capacity and voltage range during the C-rate discharge rate capability test. Results were above the specified capacity of 106.4 Ah on all three cycles.

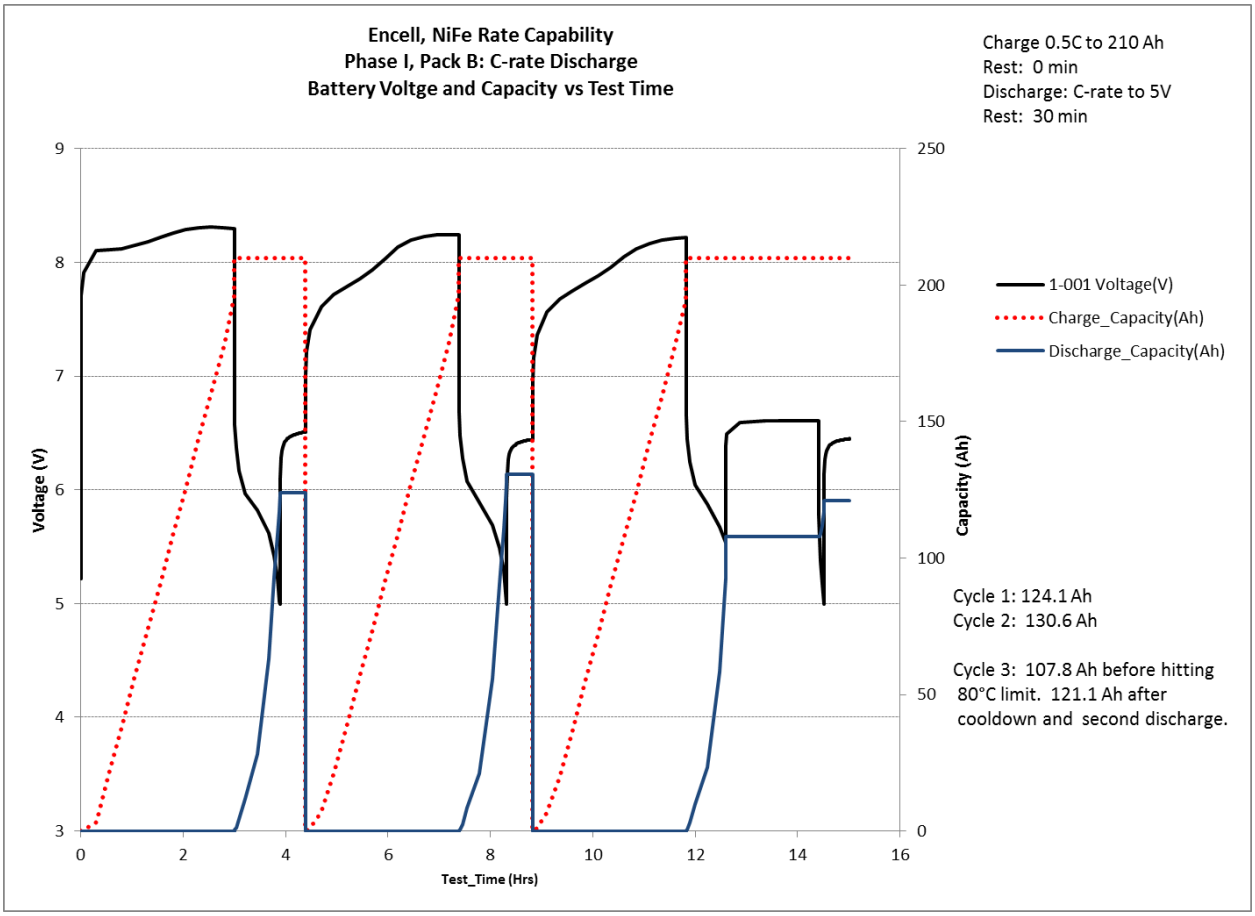

Figure 6. C-Rate Discharge Rate Capability

4.1.3 0°C Temperature Test

Three of fifteen cycles of the 0°C Temperature Test sequence were completed during the Phase I test program. Results were below the specified capacity of 106.4 Ah. The test was successfully completed with test results above the specified capacity during the Phase II test program (see Section 4.2.3).

4.1.4 40°C Temperature Test

Figure 7 shows the Ah capacity and voltage range during the 40°C Temperature Test. Results were above the specified capacity of 133 Ah on all three cycles.

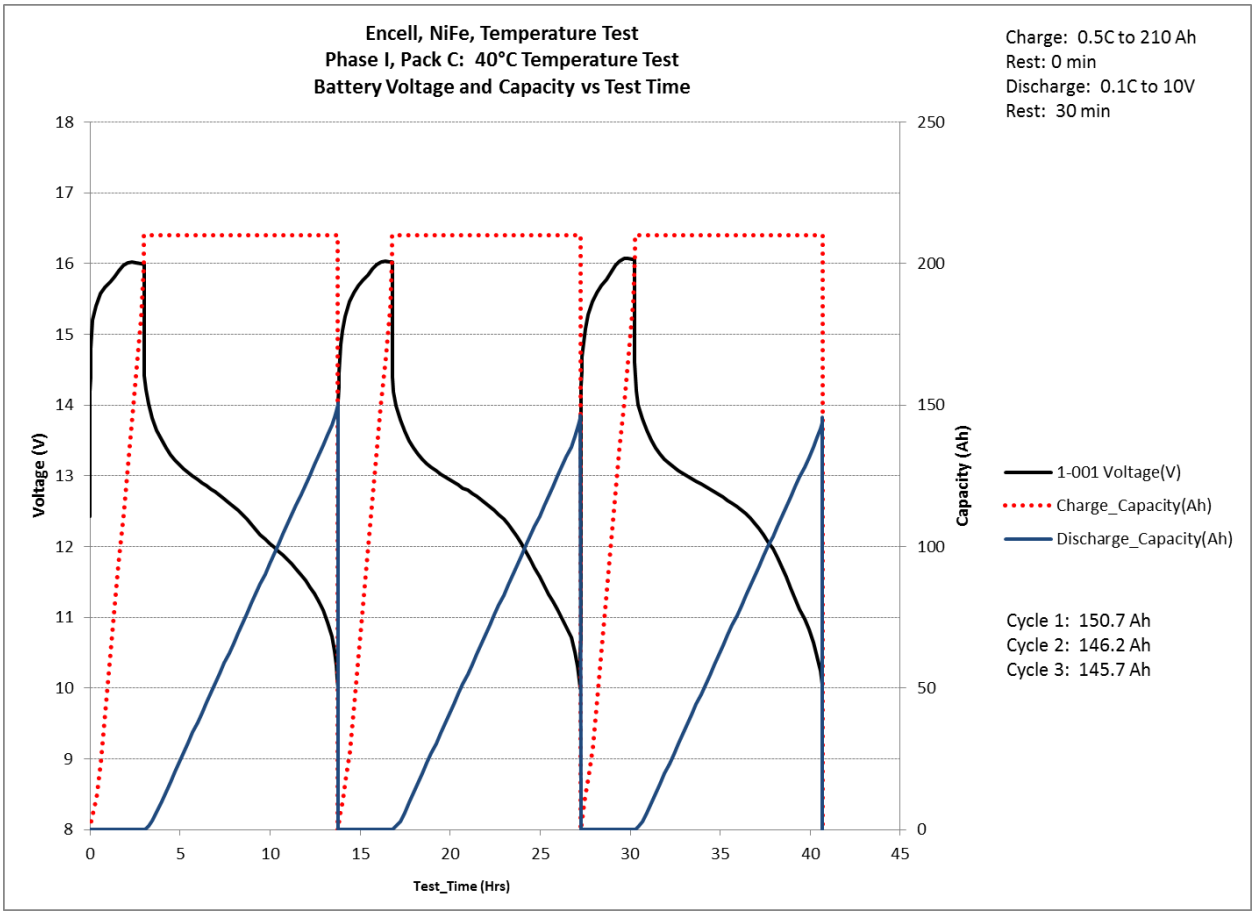

Figure 7. 40°C Temperature Test

4.1.5 28-Day Charge Retention

Results of the 28-Day Charge Retention test during Phase I test program was 108 Ah, which is below the specified capacity of 119.7 Ah. The charge retention test was successfully completed with results above the specified capacity during Phase II test program (See Section 4.2.5).

4.1.6 Gassing/Refill Test

Specified capacity for this test was the electrolyte level being above the refill line when measured four hours following the final discharge. Four hours after the final discharge, the electrolyte level was measured to be above the defined refill line. Results were above the specified capacity.

4.1.7 Accelerated Life Test

Results of the Accelerated Life Test are shown on Figure 8. The figure includes the discharge capacity of each cycle at 10V depth of discharge. Capacities ranged from 101.52 Ah (Cycle 1) to 20.22 Ah (Cycle 124). Results were above the specified capacity of 125 cycles with a capacity above 14 Ah. Encell predicts that for their battery, this translates to +3,000 cycles at application conditions (C/4 Charge, C/8 Discharge, 6-hour rest between cycles, 25°C, 100% discharge to 1.0V/cell and 80% SOC) with capacity above 70%; however, Sandia has not conducted long-term cycling under application conditions to verify life with a battery.

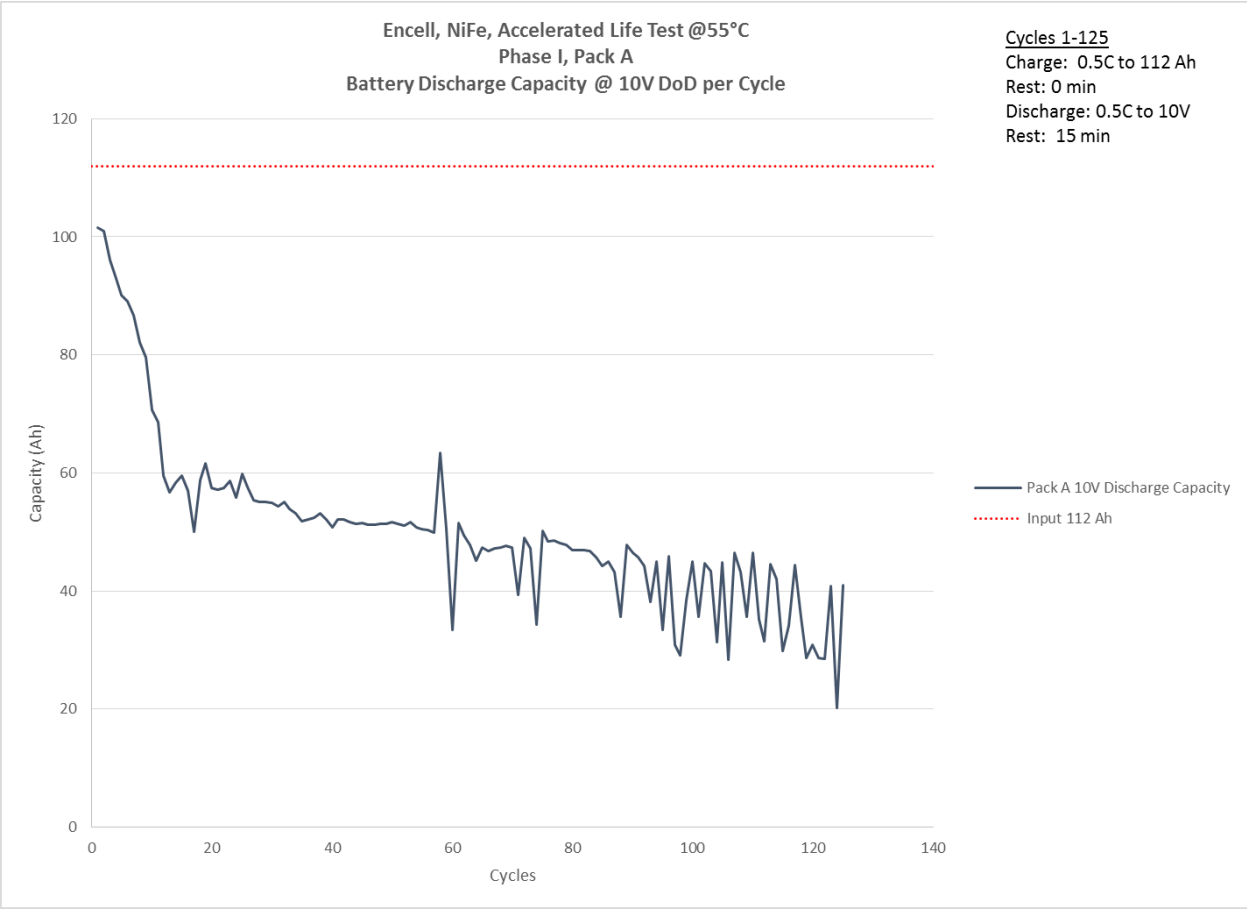

Figure 8. Accelerated Life Test

4.2 Phase II Test Results

Two 12V, 140 Ah battery packs (Module A and Module B) were used to complete the Phase II test program. The Phase II test summary is included in Section 2.0. Test procedures are outlined in Section 3.0.

4.2.1 2C Discharge Rate Capability

Figure 9 shows the ampere-hour capacity and voltage range during the 2C discharge rate capability test. Results were above the specified capacity of 106.4 Ah on all three cycles.

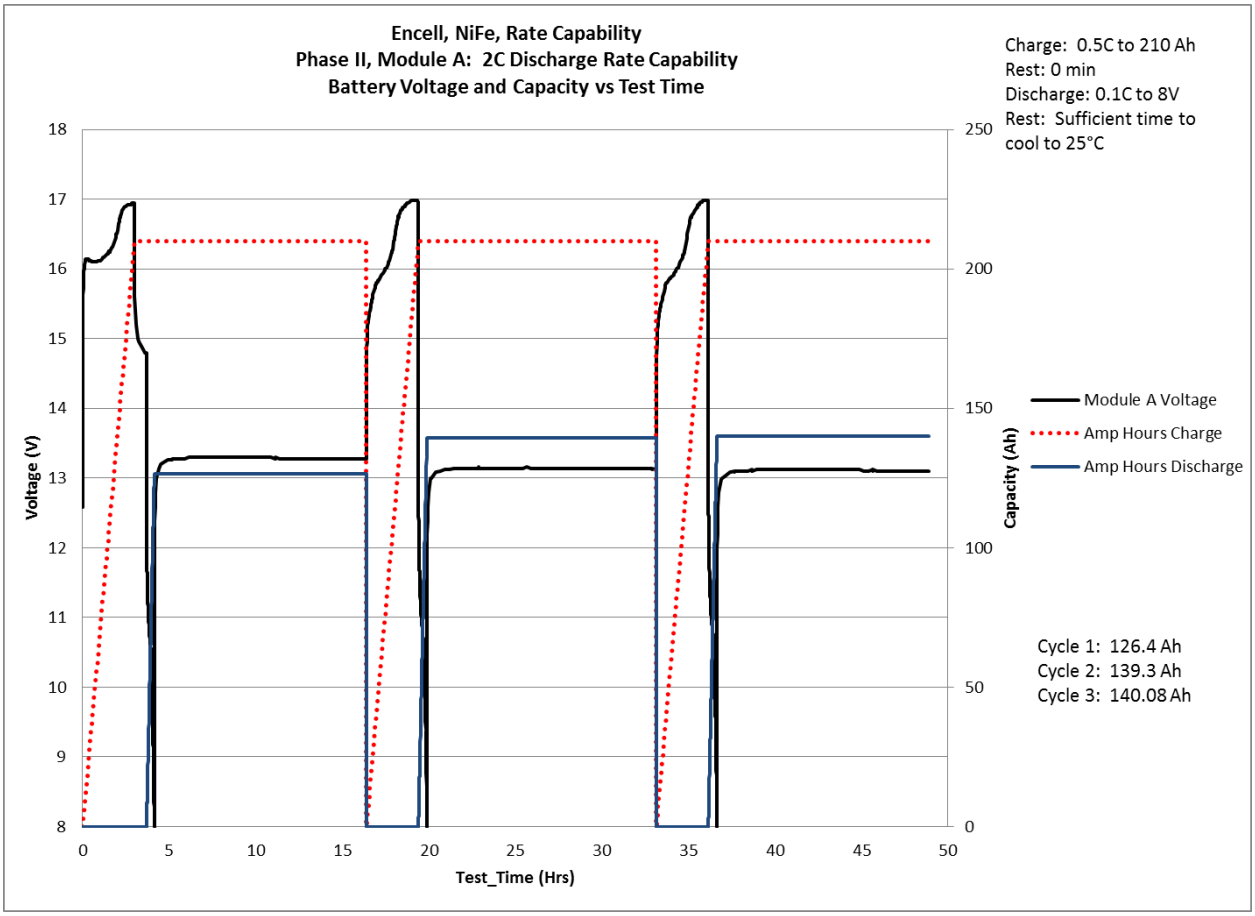

Figure 9. 2C Discharge Rate Capability

4.2.2 6C Discharge Rate Capability

Figure 10 shows the Ah capacity and voltage range during the 6C discharge rate capability test. The battery was capable of discharging the prescribed 30 Ah in each of the three successive cycles.

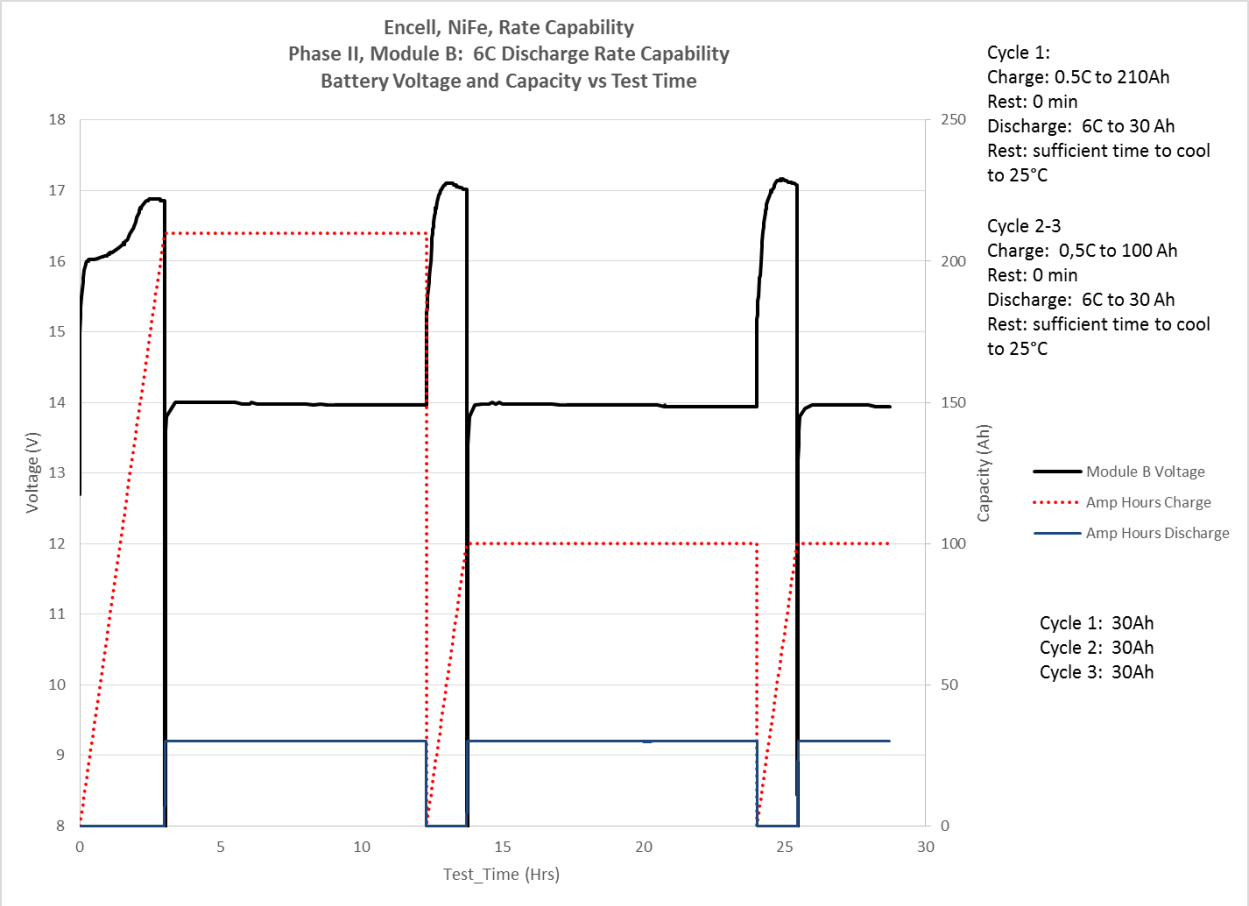

Figure 10. 6C Discharge Rate Capability

4.2.3 0°C Temperature Test

Figure 11 shows the Ah capacity and voltage range during the 0°C Temperature Test. Results were above the specified capacity of 106.4 Ah on all fifteen cycles.

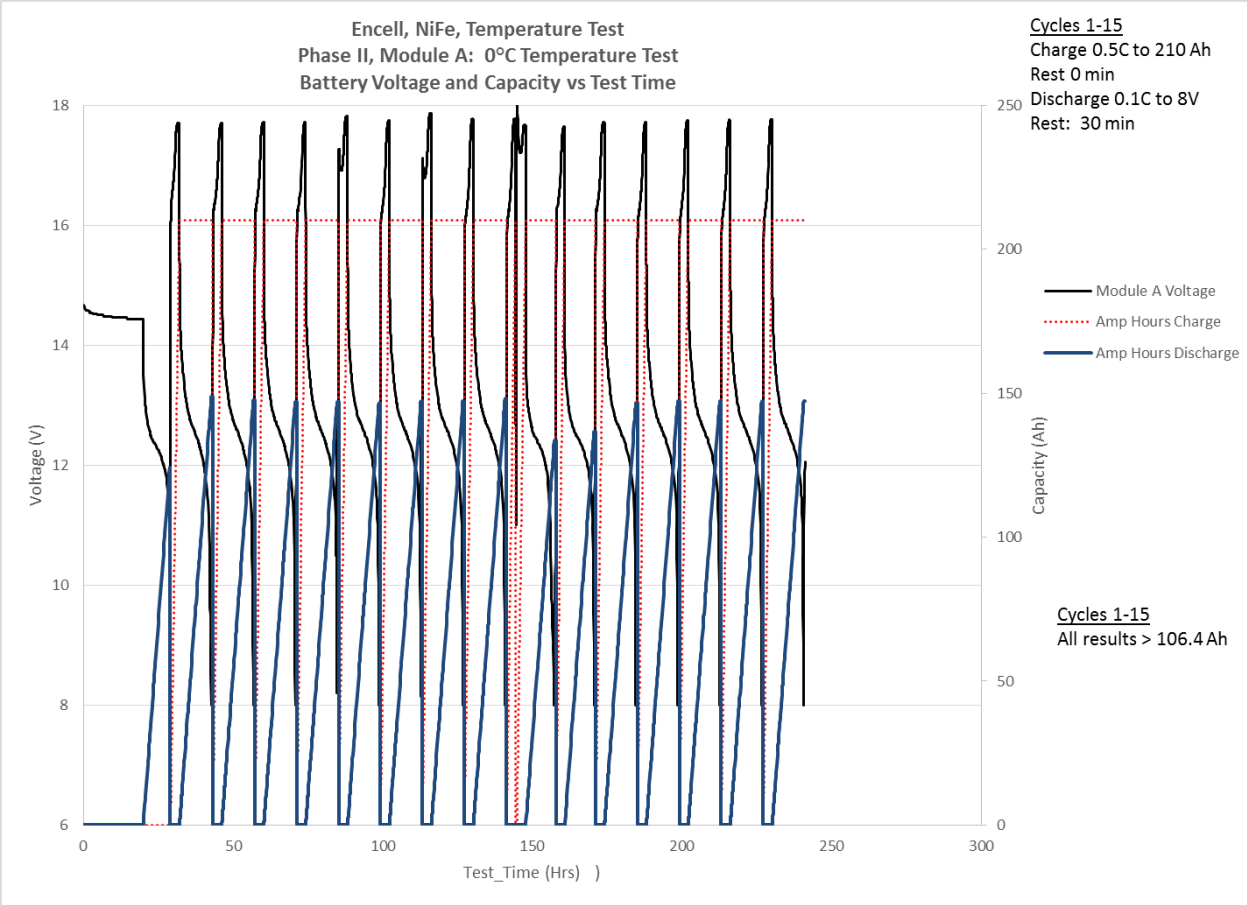

Figure 11. 0°C Temperature Test

4.2.4 80°C Temperature Test

Figure 12 shows the Ah capacity and voltage range during the 80°C Temperature Test. Results were above the specified capacity of 106.4 Ah on all three cycles.

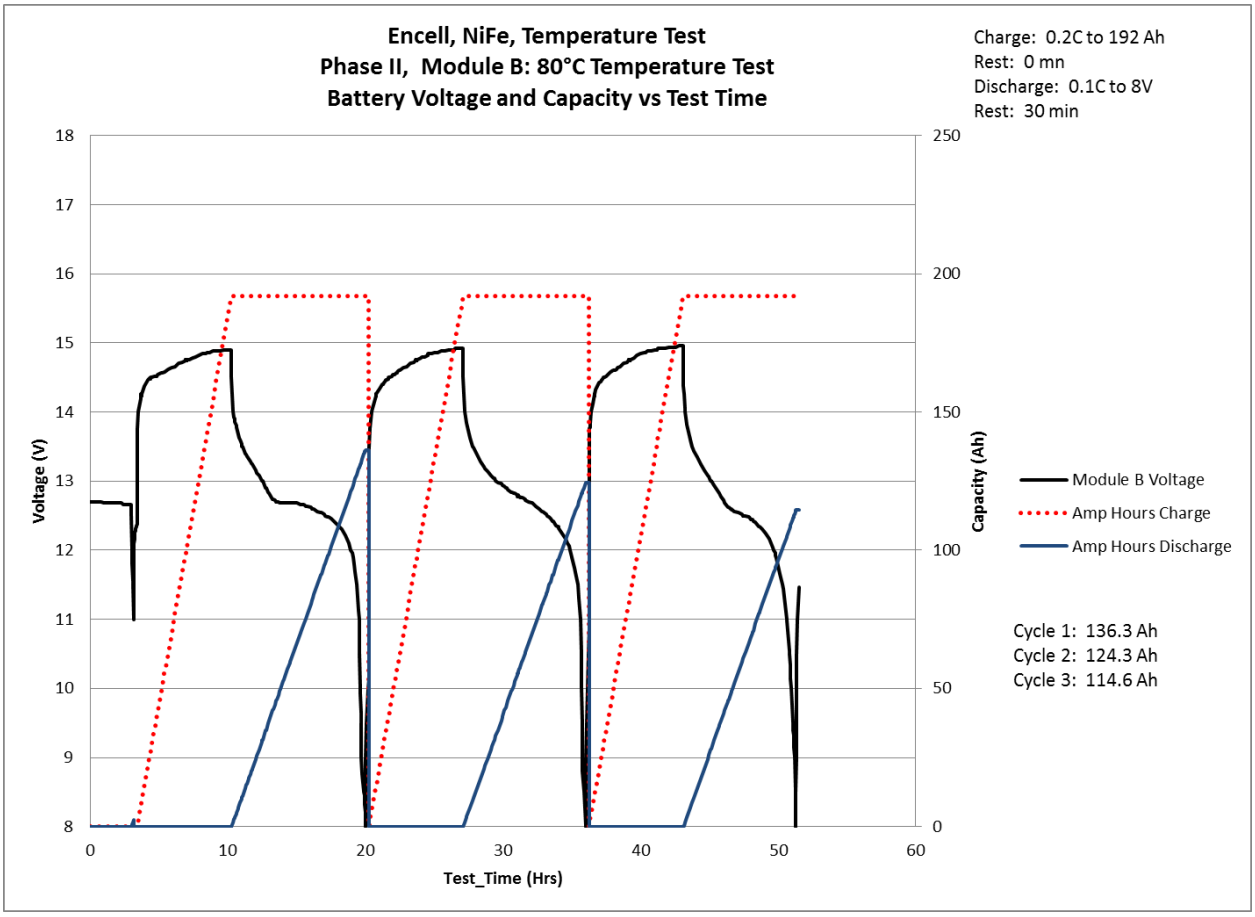

Figure 12. 80°C Temperature Test

4.2.5 28-Day Charge Retention

Figures 13 and 14 show the capacity and voltage range during the 28-Day Charge Retention. The 28-Day Charge Retention capacity result was 125.6 Ah. Results were above the specified capacity of 119.7 Ah.

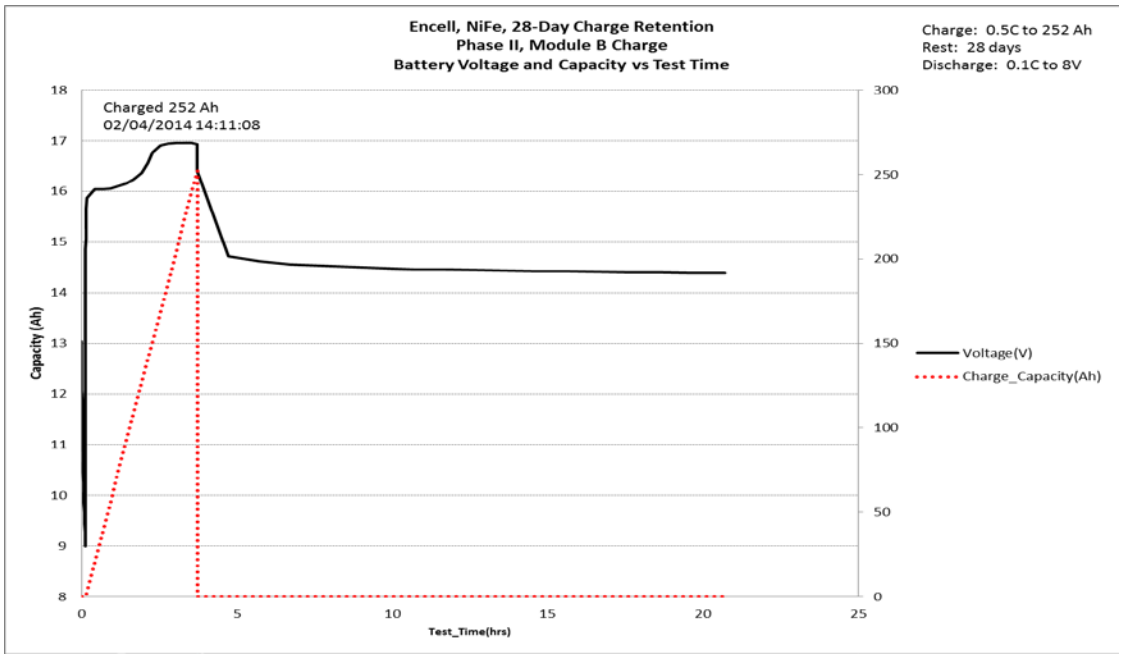

Figure 13. 28-Day Charge Retention, Charge

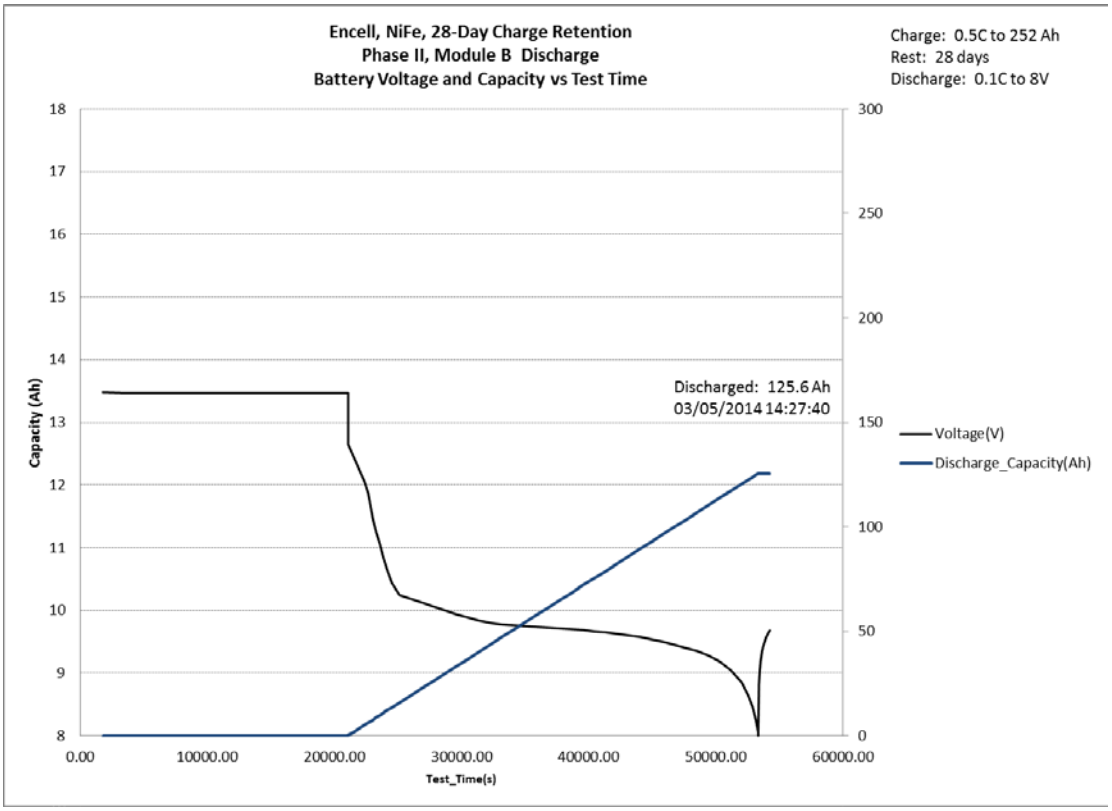

Figure 14. 28-Day Charge Retention, Charge

Furthermore, a 28-Day Charge Retention Test was run at 0°C. The measured capacity was 128.8 Ah, which was greater than the room temperature charge retention test.

5. SUMMARY

The Encell battery met the specified capacity for all characterization and performance testing. While a single pack in the Phase I testing fell just below the specified performance capacity at the C/10 rate, all other packs and modules achieved the prescribed capacity. The measured performance against rated capacity and temperature testing was as specified by the manufacturer. The self-discharge was within the prescribed limits both at ambient temperature and at 0°C. A pack cycled 30 times without refill was able to perform as expected. Finally, under an accelerated life test, the pack was able to achieve a capacity on all cycles well within the prescribed limits defined by the manufacturer. Future work looking at non-accelerated test cycling is needed to confirm that this cycling test result does translate to the 3,000 cycle life prediction for the battery. A summary of the results from both phases of testing is shown in Table 3.

Table 3. Summary of Test Results from both Phase 1 and Phase 2

Test	Phase Completed	Battery ID	Specified Performance	Measured Performance
Capacity C/10 rate	**1**	Pack A Pack B Pack C Pack D	>133 Ah	133.9 Ah 136.0 Ah 138.6 Ah 127.8 Ah
C-rate	**1**	Pack B	>106.4 Ah	107.8 Ah
2C Rate	**2**	Module A	>106.4 Ah	140.1 Ah
6C Rate	**2**	Module B	>14 Ah	30 Ah
0°C Temp	**2**	Module A	>106.4 Ah	145.7 Ah
40°C Temp	**1**	Pack C	>133 Ah	145.7 Ah
80°C Temp*	**2**	Module B	>106.4 Ah	114.6 Ah
28-Day Charge Retention	**2**	Module B	>119.7 Ah	125.6 Ah
28 Day Charge Retention 0°C	**2**	Module B	N/A	128.8 Ah
Gassing/Refill Test	**1**	Pack D	30 cycles without refill	30 cycles without refill
Accelerated Life Test	**1**	Pack A	125 cycles with capacity > 14 Ah	125 cycles with capacity of 40.9 Ah on last cycle

*Test modified from test plan referenced above charge to 137 percent of capacity to 192 Ah at a C/5 rate, or 28 A, rather than the initial test plan of 150 percent of capacity at 70 A.

6. REFERENCES

1. *Handbook of Batteries*, 4th Edition, T. B. Reddy, McGraw Hill Handbooks, 2011.

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